Journal of Archaeological Science: Reports 20 (2018) 97–114

Contents lists available at ScienceDirect

Journal of Archaeological Science: Reports

journal homepage: www.elsevier.com/locate/jasrep

Sandstone grinding/pounding tools: Use-trace reference libraries and Australian archaeological applications

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ARTICLE INFO

Keywords:
Usewear
Residues
Grinding stone
Seed grinding
Murray Darling Basin
Experimental archaeology
Sandstone

ABSTRACT

Residues, surface features and wear patterns documented on experimental and ethnographic artefacts form the foundation of residue and usewear reference libraries, from which we can interpret and evaluate the function of archaeological specimens. Here we report controlled experiments to supplement previous studies and document variables that influence usewear formation on sandstone grinding implements (including abrading stones) of different toughness and hardness. Distinct patterns of usewear result from the class of worked material, modes and duration of use, and the stone material. Hard sandstones can sustain more developed polish during use than soft sandstones, which wear more rapidly. Our experimental reference library is applied here to a pilot study of grinding implements, made of hard and soft sandstones, in archaeological contexts from southeastern Australia, where distributions of hard seed mortars and soft seed grinding stones are correlated with distinct woodland and floodplain vegetation communities, suggesting different behavioural strategies. Seed grinding is documented on both hard and soft sandstones but we suggest that grinding hard seeds is only efficient on hard sandstones. The spatial and chronological distributions of hard and soft sandstone grinding dishes are potentially linked not only with sandstone availability but also with vegetation communities and climate change.

1. Introduction

Determining the function of prehistoric artefacts is vital for reconstructing technological, subsistence and other behavioural activities of past human societies. Usewear and residue analyses provide details of specific tasks, resource-use and patterns of behaviour. Usewear traces on grinding stones in particular have provided evidence of food preparation, plant domestication, tool maintenance, symbolic expression and craft production (Table 1).

Reference libraries of diagnostic wear signatures can be generated through both 'replicative/actualistic' and 'controlled experiments' (Holdaway and Stern 2004:41). Replicative experiments are usually designed to approximate prehistoric conditions to evaluate whether particular tasks can explain, for example, the design and usewear found on archaeological tools. Controlled experiments, on the other hand, are usually designed to evaluate the role or relative importance of particular variables, which may be isolated in replicative experiments or, more often under laboratory conditions. For example, controlled experiments have been designed to isolate and assess the effects of foreign abrasive particles on usewear formation (see Kamminga, 1982) or the effects that differently shaped working edges have on tool performance and use attrition (Collins, 2008). In both kinds of experiments, the usewear documented on experimental tools thus enables improved interpretations of archaeological tool functions. Pioneering research (e.g. Anderson, 1980; Hayden, 1979; Kamminga, 1982; Keeley, 1980; Odell, 1977; Semenov, 1964) and subsequent work by many others have provided large experimental data sets for interpreting usewear and residue traces on the surfaces and edges of flaked stone tools. Analyses performed on experimental grinding stones have provided similar usewear and residue reference libraries, although they are not yet as large as flaked stone tool data sets, are less concerned with fractures and have more focus on the surface topography and features such as use-polish, striations, pits, rounding of grains, grain fractures and residues (see Table 2 for references). Australian data sets of usewear on experimental grinding stones are uncommon and dispersed in the literature (e.g. Fullagar et al., 2012, 2017; Hayes, 2015; Hayes et al., 2018). Lithic studies can overlook the significance of functional experiments, and a minor objective of this publication is to remedy the situation by making available key experimental data, for the interpretation of usewear and residues on Australian grinding implements,

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https://doi.org/10.1016/j.jasrep.2018.04.021
Received 30 November 2017; Received in revised form 16 April 2018; Accepted 26 April 2018
Available online 04 May 2018
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Table 1
Archaeological examples of grinding stone function, identified through usewear and/or residue analyses.

Grinding stone use	Reference(s)
Plant processing	
Plant food processing	Adams, 1988; Atchison and Fullagar, 1998; Aranguren et al., 2007; Del Pilar Babot and Apella, 2003; Baysal and Wright, 2005; Bofill et al., 2014; Cosgrove, 1996; Cosgrove et al., 2007; Dubreuil and Nadel, 2015; Fullagar and Field, 1997; Fullagar et al., 2006, 2008, 2015, 2017; Field and Fullagar, 1998; Field et al., 2009; van Gijn and Verbaas, 2009; Goren-Inbar et al., 2002; Haas et al., 2013; Liu et al., 2010a, 2010b, 2011, 2013, 2014; Lippi et al., 2015; Louderback and Pavlik, 2017; Mercader, 2009; Nadel et al., 2012; Pearsall et al., 2004; Piperno et al., 2000, 2004; Portillo et al., 2013; Revedin et al., 2010, 2015; Tao et al., 2011; De la Torre et al., 2013; Quigg et al., 2001; Van Peer et al., 2003; Verbaas and van Gijn, 2008; Weiss et al., 2008; Wright, 1994; Yang et al., 2012
Plant processing for fibre	Aranguren et al., 2008; Fullagar and Wallis, 2012; Hayes et al., 2018
Faunal processing	
Animal food processing	Fullagar et al., 2017; Holen et al., 2017; Stephenson, 2015; Quigg et al., 2001; Yohe et al., 1991
Preparation of hides and leather	Adams, 1988, 1989a; Cristiani et al., 2012; Dubreuil and Grosman, 2009
Processing of burnt bone	Del Pilar Babot and Apella, 2003
Polishing of bone, antler and ivory	Procopiou et al., 2011; Rosenberg and Golani, 2012
Manufacture of shell fishhooks	Attenbrow et al., 1998; Smith et al., 2015
Processing of inorganic material	
Preparation of stone material (polishing and manufacture)	Breglia et al., 2016; Caricola, 2015; Procopiou et al., 2011
Preparation of clay for pottery	Derricourt, 1986.
Preparation of pigments	Aranguren et al., 2008; Adams, 1998; Breglia et al., 2016; Caricola, 2015; Cristiani et al., 2012; Henshilwood et al., 2011; Nic, 2012; Van Peer et al., 2003

Table 2
Published usewear studies performed on experimental grinding stones, including stone material type and worked-material.

Reference	Raw material	Worked material
Adams, 1988	Sandstone, quartzite	Hide, corn
Adams, 1989a	Sandstone, quartzite	Stone, bone, wood, shell
Adams, 1989b	Sandstone	Maize kernels, sunflower seed, pottery, clay, wood, bone, hide, shell
Adams, 1993	Basalt	Stone, wood, bone, hide
Adams, 1999	Basalt, granite, sandstone, quartzite	Maize kernels, sunflower seed, amaranth seed
Adams, 2014	Basalt, sandstone	Hide, maize kernels
Adams et al., 2009	Basalt, limestone, schist, sandstone	Wheat seeds, barley seeds, rice seeds, fava beans
Aranguren et al., 2008	Unknown	Rhizomes (typha sp.)
Breglia et al., 2016	Sandstone, limestone, schist	Goethite, malachite, antler, stone, iron, copper, wood, legumes, cereals
Caricola, 2015	Sandstone, arenite, limestone	Wood, bone, skin, iron, copper, antler
Cristiani et al., 2012	Limestone, siltstone	Stone, hide, haematite/ochre
Delgado-Raack, 2008	Schist	Barley seeds
Delgado-Raack and Risch, 2009	Quartzite	Cereal seeds: bran, flour
Dubreuil and Grosman, 2009	Basalt	Hide
Dubreuil, 2002	Basalt	Wheat seeds barley seeds, nuts, acorns, mustard seeds, fenugreek, fava beans, lentils, dried meat, dried fish, ochre, shell
Dubreuil, 2004	Basalt	Ochre, domesticated wheat seeds, wild barley seeds, acorns, nuts, mustard seeds, fenugreek, fava beans, dried meat, dried fish
Fullagar et al., 2012	Sandstone, tuff	Seeds, acorns
Gilabert et al., 2012	Sandstone, limestone, quartzite, gneiss, granite	Hazelnuts, stone
Goren-Inbar et al., 2002	Basalt	Stone (flaking activities)
Hamon, 2006	Sandstone	Wheat seeds, hulled barely seeds, spelt, legumes, hazelnuts, plants, flint, bone, temper, clay, bone, antler, shell, limestone, schist, skin
Hamon, 2008	Sandstone	Wheat seeds, barley seeds, spelt, legumes, hazelnuts, plants, clay, pigment, burnt flint, burnt bone, grog, dry and wet bone, antler, shell, limestone, schist ornaments, dry and wet hide
Hamon and Plisson, 2008	Sandstone	Wheat seeds, bone, cartilage, dry meat, hide, acorn, calcite
Liu et al., 2011	Sandstone	Stone, shell, bone, haematite, bamboo, acorn, mung beans, millet seeds, oat seeds
Logan and Fratt, 1993	Sandstone	Pigment
Menasanch et al., 2002	Gabbro; schist	Wheat seeds, barley seeds
Mills, 1993	Sandstone	Volcanic stone (axe)
Procopiou et al., 1998	Quartzite	Wheat seeds, barley seeds
Procopiou et al., 2011	Corundum, sandstone	Diasporite (precious stone)
Risch, 2002	Gabbro, schist	Wheat seeds, barley seeds
de la Torre et al., 2013	Quartzite	Stone, nuts, meat, plants.
Verbaas and Van Gijn, 2008	Sandstone	Cereal seeds
Wright, 1993	Sandstone	Maize kernals
Zurro et al., 2005	Sandstone	Millet seeds

which are known to be widespread by the Late Holocene and present in Pleistocene contexts at Lake Mungo by 25–14 ka (Fullagar et al., 2015); Cuddie Springs by ~30 ka (Fullagar and Field, 1997); and Madjedbebe by ~65 ka (Clarkson et al., 2017) (see Fig. 1).

Previous experiments have shown that diagnostic usewear traces on a range of stone materials are often visible macroscopically and at low magnifications, and that, after certain periods of use, the resulting usewear patterns permit analysts to differentiate broad categories of

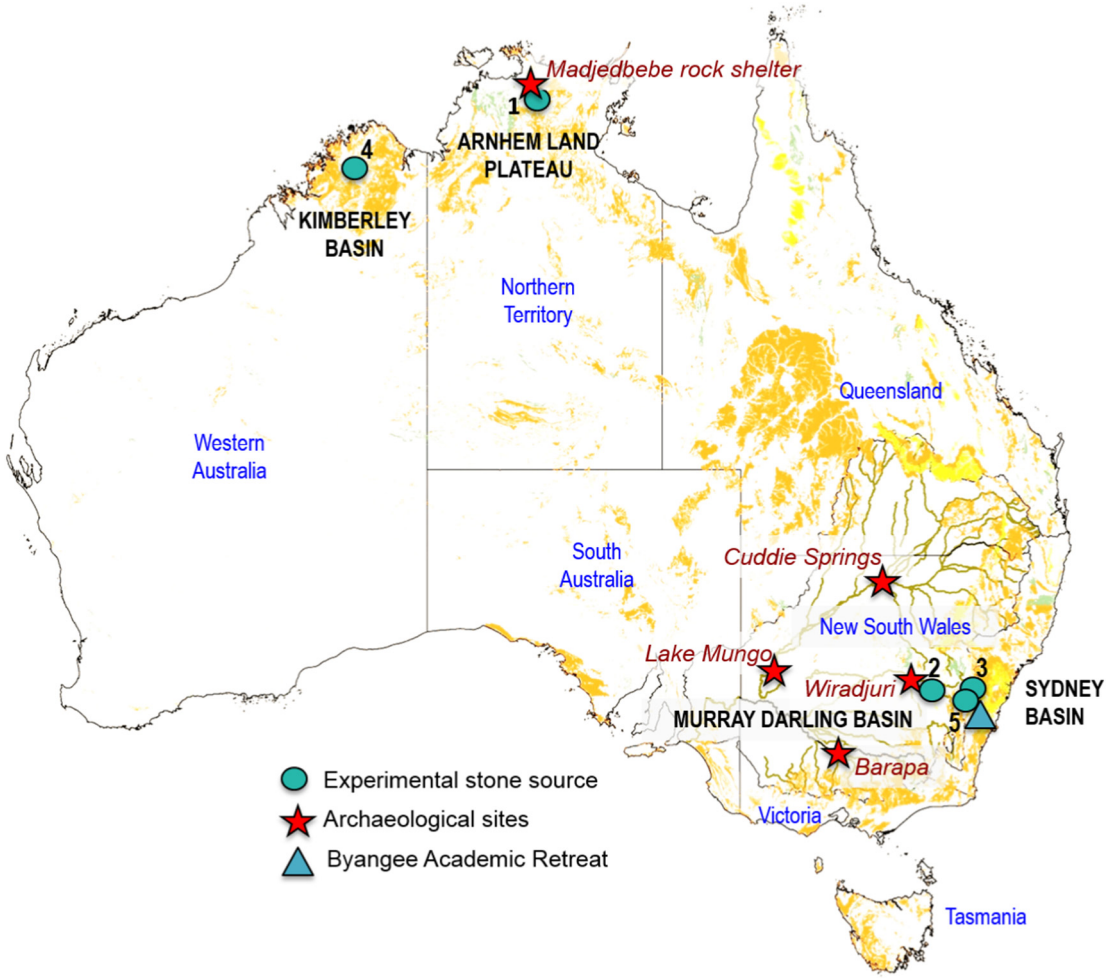

Fig. 1. Map showing the distribution of sandstone sources in Australia (coloured zones), and the locations of the four sandstone formations from which sandstone for the experimental tools was collected (green circles numbered 1–5, ordered from hardest sandstone to softest: 1, Kakadu sandstone (from the Arnhem Land Plateau); 2, Jemalong Ridge sandstone (from the Murray Darling Basin); 3, Illawarra Hawkesbury sandstone (from the Sydney Basin); 4, Kimberley sandstone (from the Kimberley Basin); 5, Bundanoon sandstone (from the Sydney Basin). The red stars indicate the archaeological sites mentioned in the text. The blue triangle indicates the location of the experimental workshop "Byangee Academic Retreat". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

worked material, including bone, stone, wood, hide, clay, shell, ochre, soft plants, and hard (e.g. Acacia) and soft (e.g. grass) seeds. This paper supplements previous functional studies with new experiments, and aims to create a more comprehensive reference library for interpreting the function of grinding, pounding and abrading implements made of different sandstone compositions from Australian contexts, where grinding stones (usually made from sandstone or quartzite) are used for a range of tasks known ethnographically. These include the processing of edible plant tissues such as grass seeds, underground storage organs (e.g. tubers and rhizomes) and other starchy plants (nardoo, water lily seed, wild rice); the opportunistic processing of animal tissues (e.g. kangaroo tail, goanna); pigment processing; and for the production and maintenance of various implements such as ground-edge axes, hatchets and blades, bone points and shell hooks (e.g. Atchison and Head, 2012; Binford 1987:459; Cane, 1989:113; Chaloupka and Giuliani, 1984; Gott, 2002; Gould 1969:19, 1980:193–194; Gould et al. 1971:163; Hayden 1979:141; Jones and Meehan, 1989; Latz, 1995; McArthur, 1960a, 1960b; McCarthy, 1976, Mitchell, 1848; Peterson, 1968:568; Smith 1985:24).

Here, we describe usewear and residue data from 28 experimental grinding tools made from five Australian sandstone sources of variable composition, and present the results of a pilot study involving the analysis of two grinding stone assemblages from southeastern New South Wales. The success and limitations of the current reference libraries are discussed with reference to specific archaeological applications.

2. Background: usewear on grinding stones

Residues and wear on stone artefacts can originate from a mix of sources; some being use-related tasks, and others incidental contact and non-cultural agencies. Dubreuil et al. (2015) describe seven stages that encompass the life history of a stone tool that influence the development and accumulation of specific types of wear: 1) raw material choice and procurement; 2) manufacture; 3) primary use; 4) secondary use; 5) recycling; 6) discard; 7) post-depositional processes.

Building on the research of tribologists who study wear, friction, and lubrication, Adams (1988, 1993, 2002a, 2002b, 2014) distinguishes four mechanisms responsible for the formation of usewear on ground surfaces: (1) adhesive wear; (2) abrasive wear; (3) fatigue wear and (4) tribochemical wear. *Adhesive wear* results from contact between two surfaces in which molecular interactions are taking place, causing the formation and breaking of bonds at an atomic level. *Abrasive wear* occurs when loosened particles become abrasive agents in the wear process, either in the depositional environment, through contact with sediments, environmental contaminants and other debris; or from use,

resulting from the removal of surface particles in the stone or abrasive agents within the worked material. *Fatigue wear* is a mechanism that occurs when the artefact pressure, impact, or the alternating stress of movement is applied to the stone surface, resulting in crushing, cracks and pits on the stone surface. *Tribochemical wear* is a combination of mechanical and chemical interactions that may cause the build-up of films and oxides resulting in an additive surface polish or sheen, such as the silica polish described by Kamminga (1979) and Fullagar (1991). Polish is typically viewed at higher magnifications using vertical incident light, and is observed on individual grains. Tribochemical wear and polish can be visible to the naked eye on heavily used stone surfaces. This polish will be more developed and form faster on stones with smoother (less granular) textures (e.g. quartzite, basalt) because their surfaces are smoothed faster, with less stone debris to inhibit polish formation (Adams, 2014).

Wear formation on archaeological tools begins during manufacture, when stone artefacts are produced usually by stone-on-stone contact. Although wear may be dominated by primary and secondary use, there are seven stages within an artefact life history that may lead to the accumulation and modification of wear traces (Dubreuil et al., 2015). Of particular interest here are the wear traces generated during use, but first we briefly discuss wear from manufacture. After discussing traces of use, we then discuss taphonomic/post-depositional processes.

2.1. Manufacture

Grinding stones are sometimes quarried, manufactured and shaped from blanks to facilitate transport as well as the intended grinding activity. For example, Australian millstones were often prepared at the quarry by using a hammer to remove rough debris from the surface, and by flaking the edges to reduce its size for travel and to optimise its shape for seed grinding (McBryde, 1997; Mulvaney, 1998). This preparation or manufacturing stage occurs among many groups who use grinding/milling implements. For example, the preparation of Linearbandkeramik grinding stones in the European Neolithic often involved similarly elaborate preparation accomplished by flaking, pecking and smoothing (Hamon 2008:1504).

The preparation or initial shaping of grinding tools using a stone hammer or file will introduce wear traces that might be confused with traces from actual use of the implement. For example, stone-on-stone grinding often leaves distinctive wear traces in the form of deep furrows and highly levelled grains leaving the interstices un-altered (Adams 1989a:267; 1993:68; Dubreuil 2004:1616). Stone-on-stone wear may originate during the manufacturing stage and/or during actual use (e.g. grinding stone axes). It is therefore essential that manufacturing traces form part of the analytical process.

2.2. Use

Grinding stones and abrading tools can display distinct forms of usewear that may be diagnostic of function. Surface modifications resulting from deliberate contact with a specific worked material can be related to Adams' four wear mechanisms and the macro- and micro-topography of the ground surface relative to an unworn surface, where 'micro-topography' refers to the microscopic elevation or relief observed on the artefact surface (Adams et al. 2009:28). Usewear on abrading tools (tools that are used to remove part of a surface by rubbing, hereafter filing stones) results predominantly from reductive processes whereby the micro-relief of the used surface becomes smoothed, and individual grains are levelled and/or highly rounded (Dubreuil et al. 2015:137). Grain modification is most extensive on the highest points of the working surface, sometimes forming a plateau and highly levelled areas that are interconnected. Usewear on percussive tools (hammerstones and anvils) includes impact marks, macro and micro-scarring of individual grains, breakage and patches of abrasion (Dubreuil et al. 2015:134). Other wear features that may be present on filing or percussive stones include striations, use-polish, and any residues or rock debris remaining within the interstices (interstices between grains) on the artefact surface (e.g., Adams 1988:311–312; Adams et al. 2009:47–53; Dubreuil, 2004; Hamon 2008:1506).

The appearance of specific usewear features on ground-stone tools is related to the intensity and duration of use, the properties of the material being worked (including texture, hardness, toughness, moisture content, etc.) and additional properties of the grinding stone surface (mineralogy of the stone material, durability, asperity, texture and cementation) (Adams 1993:61–2, 2014:130; Adams et al. 2009:53; Delgado-Raack and Risch 2009:9; Hamon 2008:1504). Other microscopic features of ground-stone tool surfaces include: (1) surface damage in the form of grain extraction; (2) micro-fracturing; (3) the appearance of surface pits and cracks; and (4) use-polish or 'sheen' (Adams et al. 2009:46). The latter may be characterised in terms of polish distribution, morphology (e.g. reticulated, undulating), brightness and connectedness; and will vary depending on the worked material and intensity/duration of use. Use-polish on sandstone grinding tools is often documented for individual quartz grains, and develops in much the same way as has been documented for quartz tools (see Fullagar, 1986; Knutsson, 1986; Knutsson et al., 2015 for descriptions).

2.3. Taphonomic traces

Taphonomy is the study of biological, chemical, erosional and other processes within an archaeological deposit, and these processes may result in alterations to use-residues and the build-up of non-use related residues and surface alterations to buried stone tools. In situ taphonomic residues on stone tools include oxide accretions and surface patina, caused by soil chemistry; organisms, including fungal hyphae; and the transfer of other soil constituents (e.g., starch grains). Tool surface alterations may result from taphonomic processes such as solifluction, bioturbation and other movements of sediment that can cause striations and other traces unrelated to use (Burroni et al. 2002:1278; Keeley 1980:28; Keeley and Newcomer 1977:35). Mechanical and chemical weathering can also potentially alter and remove traces of use, including both residues and polish (e.g. Plisson and Mauger 1988:4).

Usewear may be distinguished from taphonomic traces on the basis of distribution, abundance, location on the tool and other contextual evidence such as residues (Kononenko 2011:7; Tringham et al., 1974). Wear traces that have no distributional patterning or directionality consistent with experimental usewear data are more likely the result of either post-depositional processes or natural weathering prior to deposition.

Post-depositional and post-excavation effects can potentially mimic traces of use, and previous experimental work has investigated mechanical and chemical weathering, movement of sediment and starch grains within the depositional environment; sieving and artefact handling; transportation following excavation; artefact cleaning; and artefact storage (Table 3). Both replicative and controlled experiments have been indispensable for reliable interpretations of usewear and residues.

3. Materials and methods

A set of experimental artefacts was designed to complement previous replicative experiments and document usewear patterns from processing different classes of material, including selected Aboriginal resources known ethnographically. Methods of analysis followed conventional techniques for identifying usewear and residues.

3.1. Experimental design

The experiments were not designed to be comprehensive or to evaluate the wear generated from other stages in the life history of the tools (manufacture, curation, discard and post-depositional processes).

Table 3
Published replicative and controlled experiments for assessing wear and residues from non-cultural agencies.

Replication exp.	Reference(s)
Mechanical and chemical weathering	Burroni et al., 2002; Cattaneo et al., 1993; Eisele et al., 1995; Gurfinkel and Franklin, 1988; Hardy and Raff, 1997; Keeley 1980:28–35; Langejans, 2010, 2011; Levi-Sala, 1986a, 1986b; Lombard and Wadley, 2007; Plisson and Mauger, 1988; Wadley et al., 2004
Movement of seeds and starch grains in the depositional environment	Burroni et al., 2002; Keeley 1980: 34; Therin, 1998, 2006
Trampling	Domínguez-Rodrigo et al., 2009; Flenniken and Haggerty, 1979; Gifford-Gonzalez et al., 1985; Kamminga, 1982; Keeley 1980:34; McBrearty et al., 1998; Pryor, 1988; Shea and Klenck, 1993; Tringham et al., 1974
Sieving	Gero, 1978; Kamminga, 1982
Artefact dropping	Moss, 1983
Transportation following excavation	Kamminga, 1982
Artefact cleaning	Evans and Donahue, 2005; Evans and Macdonald, 2011; Gero, 1978; Neumann and Sanford, 1998
Artefact storage	Barton, 2007; Gero, 1978

Table 4
Summary of stone materials used in experimental grinding workshop, relative hardness and average grain size. Relative hardness was determined by the percentage of quartz and clay minerals present and the degree of cementation following XRD and SEM analysis.

Sandstone source/ location	Geological Formation	Lithological Description	Relative hardness	% Quartz	Size range of quartz grains	Other minerals present
Jemalong, NSW	Jemalong Ridge	Strongly cemented, high cohesion, well sorted fine-grained quartz, poorly crystalline illitic clays, rounded grains	1	95.7	80–150 μm	Kaolin 0.9% Illite 3.4%
Kakadu, NT	Kombolgie	Strongly cemented, high cohesion, well sorted fine-grained quartz, crystalline illitic clays, rounded grains	2	96.9	150–200 μm	Kaolin 0.2% Illite 2.9%
Illawarra, NSW	Hawkesbury	Strongly cemented, high cohesion, poorly sorted quartz, crystalline illitic and kaolinite clays, rounded grains	3	95.4	200–400 μm	Kaolin 2.6% Illite 1.8% Mixed illite 0.2%.
Kimberley, WA	Yampi	Strongly cemented, moderate cohesion, coarse-grained poorly sorted quartz, poorly crystalline kaolinite clays, rounded grains	4	90.4	80–400 μm	Calcite 0.1% Kaolin 5.3% Illite 3.9% Mixed illite 0.3%
Bundanoon, NSW	Hawkesbury	Loosely cemented, low cohesion poorly sorted quartz, poorly crystalline kaolinite clays, rounded grains	5	77.7	150–400 μm	Kaolin 19.7% Illite 2.4% Mixed illite 0.2%

Twenty-eight grinding stones (EGS) were used in 19 controlled experiments to assess particular variables, particularly sandstone hardness. These came from five locations, one in Arnhem Land and the others in the Murray Darling Basin (Fig. 1, Tables 4 and 5). Ten stones were used individually (i.e. as passive filing stones to sharpen or shape a given material, including one tool that was used on two surfaces). The rest were partnered as dedicated upper and lower (cf. active and passive) pairs to process an intermediate material (n = 18; Table 5). Stones were used individually as files or as paired grinding stones to replicate a range of known Aboriginal grinding activities. Processing actions included grinding, pounding and filing and processing times ranged from 10 min to 4 h (Table 5). Processing times varied depending on the stone material selected (certain stones were more effective at processing some materials) and the material worked (harder seeds required longer processing times). Some stones from the same source were intentionally used to work the same material for different durations, to document different stages of wear development and assess operator variance. All experiments were conducted outdoors with bare hands by one of five experimenters.

3.1.1. Sandstone

Each of our experimental tools was made from one of five sandstones obtained from four regions/geological formations in Australia. These include stone from the Yampi Formation in the Kimberley Basin in northern Western Australia; stones from the Kombolgie Formation in the Arnhem Land Plateau, Northern Territory; two sandstones from the Hawkesbury Sandstone Formation from different regions of the Sydney Basin in southern New South Wales; and one sandstone from Jemalong Ridge in the Murray Darling Basin in mid-western New South Wales (Fig. 1). The sandstones varied in hardness, toughness and durability (as determined by the ratio of quartz and its softer cementing matrix), as well as texture and composition (as determined by the size of quartz grains) and porosity (as determined from images made with the scanning electron microscope (SEM) (Table 4; Fig. 2). Sandstones were selected specifically from some of these regions because of archaeological research into the function of grinding, pounding and abrading sandstone tools at or near these locations (e.g. Hayes, 2015). Usewear documented on experimental sandstone stools is therefore applicable to local archaeological specimens. The effects on usewear from variation in hardness, toughness, texture and composition (Table 4), may also be relevant to understanding other sandstone tool kits.

Specific stones were collected on the basis of surface availability and suitability for experimental work (i.e. shape, weight). The hardness, toughness, texture and composition of the sandstones help to determine the efficacy of varying sandstone materials for particular tasks, and to understand the accumulation, recognition and diagnostic specificity of usewear (for discussion, see Delgado-Raack et al., 2009; Dubreuil et al. 2015:116–120).

3.1.2. Manufacture of experimental tools

Most stones (n = 16) were unmodified prior to use, to avoid introducing manufacture traces and had naturally weathered cortical surfaces and naturally rounded grains. Three stones (EGS 31, EGS 19 and EGS 24) were prepared prior to use. EGS 31, a lower stone that was used to grind warrego grass seeds (Experiment No. 6), was manufactured from Jemalong Ridge sandstone (Table 5). Preparation involved 30 min of surface smoothing with an upper abrasive stone (discarded after use) to flatten the surface topography. EGS 19 and EGS 24 are paired stones that were used to pound dry kurrajong seeds (Experiment No. 11), and were manufactured from Hawkesbury

Table 5
Experimental sandstone tools, their features and details of experiments.

Exp. #	Stone #	Sandstone source	Artefact type	Dimensions (mm) length, width, height	Mass	Cross section of grinding surface	Worked-material	Stroke type/motion	Use duration (min)
1	EGS 3	Bundanoon	Abrading stone	220, 120, 33	1189 g	Flat	Bone	Filing/back-and-forth	120
2	EGS 5	Kakadu NP	Handstone	130, 114, 30	416 g	Undulating	Bone	Filing/back-and-forth	120
3	EGS 20	Illawarra	Anvil	205, 200, 85	5400 g	Flat	Bone	Pounding	30
3	EGS 34	NSW river cobble	Pestle	112, 76, 76	909 g	Convex	Bone	Pounding	30
4	EGS 2	Kakadu NP	Abrading stone	117, 88, 32	404 g	Undulating	Wood	Filing/back-and-forth	120
5	EGS 4	Bundanoon	Abrading stone	121, 119, 36	819 g	Flat	Wood	Filing/back-and-forth	120
6	EGS 16	Bundanoon	Millstone	305, 274, 43	5900 g	Flat	Kangaroo grass seeds	Grinding/back-and-forth	90
6	EGS 29	Jemalong Ridge	Handstone	120, 82, 31	735 g	Flat	Kangaroo grass seeds	Grinding/back-and-forth	90
7	EGS 12	Bundanoon	Millstone	470, 370, 80	16.3 kg	Flat	Warrego grass seeds	Grinding/back-and-forth	240
7	EGS 28	Jemalong Ridge	Handstone	125, 75, 38	574 g	Convex	Warrego grass seeds	Grinding/back-and-forth	240
8	EGS 31	Jemalong Ridge	Millstone	4030, 3010, 80	14 kg	Flat	Warrego grass seeds	Grinding/back-and-forth	150
8	EGS 33	Bundanoon	Pestle	38, 59, 20	221 g	Flat	Warrego grass seeds	Grinding/back-and-forth	110
9	EGS 23	Jemalong Ridge	Handstone	110, 85, 64	944 g	Convex	Acacia seeds	Grinding/back-and-forth	120
9	EGS 32	Jemalong Ridge	Millstone	210, 150, 60	3065 g	flat	Acacia seeds	Grinding/back-and-forth	120
10	EGS 17	Illawarra	Millstone	285, 162, 55	4313 g	Flat	Acacia seed	Pounding + grinding	120
10	EGS 25	Jemalong Ridge	Handstone	90, 73, 47	415 g	Convex	Acacia seeds	Pounding + grinding	120
11	EGS 19	Illawarra	Mortar	200, 190, 45	2177 g	Undulating/flat	Kurrajong seeds	Grinding/back-and-forth	150
11	EGS 24	Jemalong Ridge	Handstone	388, 72, 37	392 g	Convex	Kurrajong seeds	Grinding/back-and-forth	150
12	EGS 1	Kakadu NP	Abrading stone	118, 88, 28	323 g	Flat	Wheat kernels	Grinding/back-and-forth	75
12	EGS 15	Bundanoon	Millstone	375, 350, 75	14.4 kg	Flat	Wheat kernels	Grinding/back-and-forth	75
13	EGS 11	Bundanoon	Millstone	Not available	–	Undulating/flat	Coffee beans	Grinding/back-and-forth	30
13	EGS 37	Bundanoon	Handstone	128, 100, 55	1017 g	Convex	Coffee beans	Grinding/rotary	30
14	EGS 13/1	Bundanoon	Abrading stone	547, 308, 40	10.8 kg	Undulating/flat	Stone (basalt)	Filing/back-and-forth	60
15	EGS 13/2	Bundanoon	Abrading stone	547, 308, 40	10.8 kg	Undulating/flat	Stone (dolerite)	Filing/back-and-forth	80
16	EGS 18	Kimberley	Abrading stone	190, 190, 50	2108 g	Flat	Stone (basalt)	Filing/rotary	60
17	EGS 38	Kakadu NP	Abrading stone	Not available	–	Undulating	Stone (sandstone)	Grinding/back-and-forth	20
17	EGS 39	Kakadu NP	Abrading stone	Not available	–	Undulating	Stone (sandstone)	Grinding/back-and-forth	20
18	EGS 35	Kakadu NP	Abrading stone	125, 85, 38	680 g	Flat	Haematite	Filing/back-and-forth	10
19	EGS 36	Kakadu NP	Abrading stone	170, 70, 40	369 g	Flat	Haematite	Filing/back-and-forth	97

sandstone and Jemalong Ridge sandstone, respectively. Preparation involved use of the upper stone (EGS 24) to pound the surface of the lower stone (EGS 19) for 30 min to create a central depression to aid the pounding of the seeds. Traces resulting from manufacture were documented on each of these stones prior to use.

3.1.3. Processed materials

The experimental tools were used to process 12 materials with three actions (circular and back-and-forth grinding, pounding and filing actions) to replicate Aboriginal uses of grinding stones (Table 5). Processed materials included taxa known to have been ground ethnographically: fresh bone (kangaroo femur—*Macropus fuliginosus*), fresh Australian hardwood (mulga—*Acacia* sp.), Australian seeds from kangaroo grass (*Themeda australis*), warrego grass (*Setaria jubiflora*), Acacia (*Acacia decora*), and kurrajong (*Brachychiton sp.*); and locally sourced Kakadu haematite. Two other materials (wheat (*Triticum* sp.) kernels and coffee beans) were ground in order to make comparisons with wear patterns from processing the much larger seeds documented in other regions of the world. Volcanic stones (e.g. dolerite, basalt) and sandstone were also ground in order to replicate the preparation of stone axes and document the wear associated with stone-on-stone activity.

The activities were grouped by material and action as follows: bone filing, bone pounding, wood filing, haematite grating, stone filing, seed grinding and pounding.

3.2. Analytical methods

3.2.1. Microscopy

Before use, each sandstone grinding slab was examined microscopically using a portable Dino-Lite™ digital microscope (Model: Premier AD-7013MZT) equipped with a 5.0 megapixel sensor and up to 2592 × 1944 pixels of resolution, allowing for magnifications of ×30–×230. Several high-magnification images were captured before, during and after episodes of use, so that usewear development could be documented and compared to images of the original, unaltered surface. Polyvinyl siloxane (PVS) peels were collected from the artefact surface prior to use and at regular intervals throughout use so that the progressive development of usewear could be documented. The PVS compound provides a high-resolution negative impression of the artefact surface that may then be examined under magnifications of up to ×500. Following use, all tools were examined under low magnification (×6.7 to ×45) using an Olympus SZ61 stereomicroscope with an external fibre optic, 150 W halogen light source (Olympus LG-PS2) and a Leica MZ16A stereomicroscope with an automatic Z-stacking function. Multifocal images were obtained using a DFC320 Leica camera and stitched to create a focused image using Leica LAS V4.4 software. Tool surfaces and PVS peels were then examined under high magnification using an Olympus metallographic microscope (model BX51) with vertical incident light (brightfield and darkfield), polarising filters, and

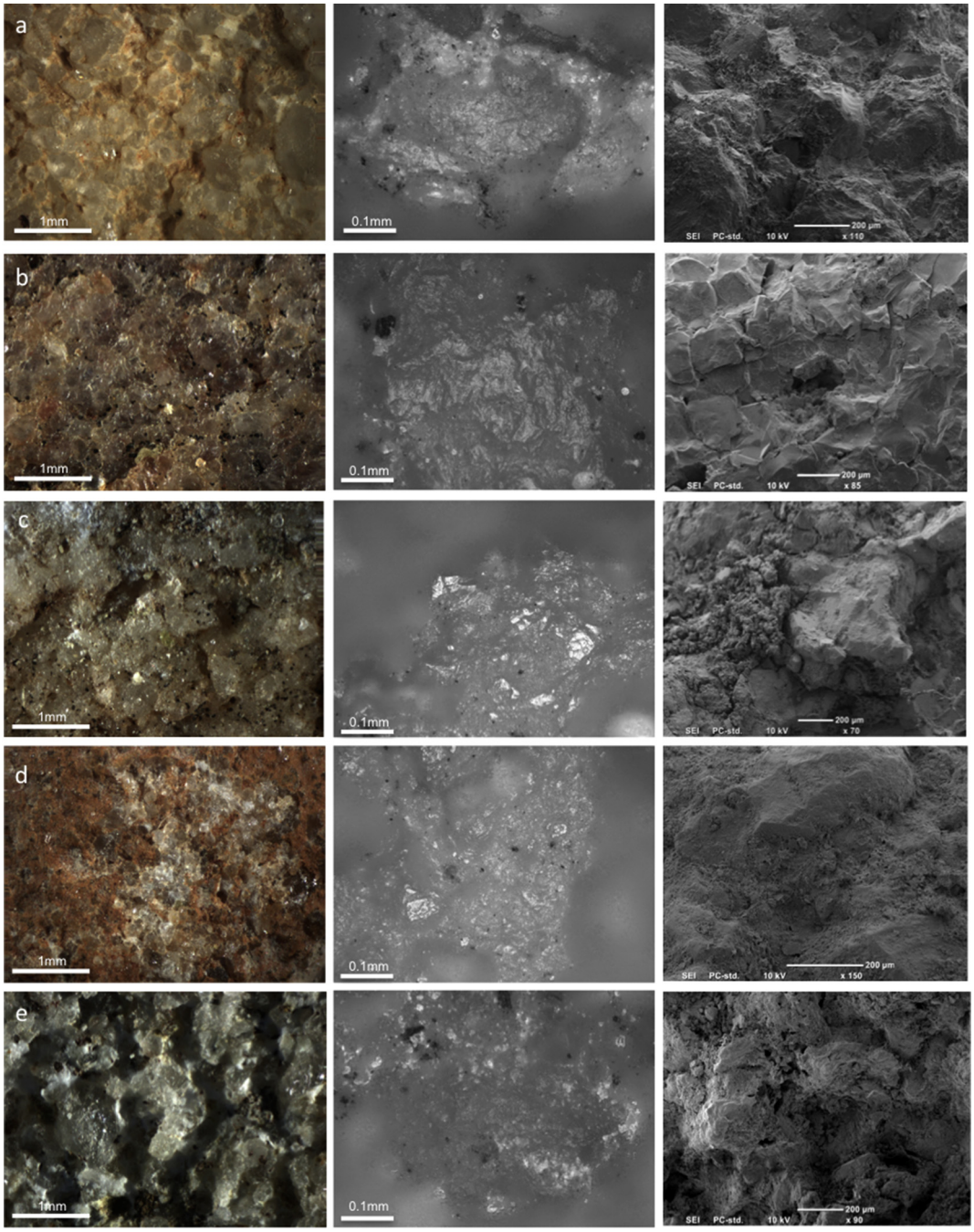

Fig. 2. Low magnification, high magnification and SEM images of unground sandstone surfaces used in the experimental workshop, in order of relative hardness: a) Kakadu sandstone/quartzite, Northern Territory: well cemented, fine-grained quartz grains, illitic clays; b) Jemalong Ridge sandstone, New South Wales: well cemented fine grain quartz with illitic clays (poorly crystalline); c) Hawkesbury sandstone from the Austinmer region, New South Wales: illitic and kaolinite bundles, poorly sorted quartz; d) sandstone from the Kimberley region, Western Australia: poorly crystaline clays, possibly some kaolinite; coarse grained and poorly sorted quartz; e) Hawkesbury sandstone from Bundanoon, New South Wales: poorly cemented, poorly crystalline clays, mostly kaolinites, poorly-sorted quartz.

objective lenses of ×5, ×10, ×20, and ×50 magnification.

3.2.2. Sandstone analysis

Sandstone hardness was determined from the visual identification of constituent minerals using the SEM (Fig. 2) and the compositional structure using X-ray diffraction (XRD). These analyses provided a relative ranking for hardness based on the relative proportion of quartz in the sandstone matrix and the degree of cementation as well as the ratio of kaolin and illite minerals making up the cementing matrix (Table 4). Sandstones with higher percentages quartz are typically harder, while those with cementing matrix of illite with be better cemented than those with higher kaolin minerals. High magnification photos of the stone surface taken with the SEM also indicate the porosity of the stone and the shape/angularity of the quartz grains (Fig. 2).

3.2.3. Usewear and residues

Usewear features were described according to characteristics suggested by previous investigators (e.g. Adams, 1989a; Adams et al., 2009; Dubreuil, 2004; Hamon, 2008) and included as documented with a stereomicroscope: (1) grain rounding; (2) surface levelling; and (3) striations; and at high magnification documented with a vertical incident light microscope: (4) use-polish brightness; (5) use-polish

Table 6
Wear features identified with the stereomicroscope (oblique incident light) and the metallographic (vertical incident light) microscope under.
Adapted from Adams et al. (2009).

Variable	Description
Stereomicroscope (oblique incident light)	
1. Grain rounding	Absent, minimal, moderate, high
2. Surface levelling	Absent, minimal (disconnected), moderate, high (connected)
3. Striations	Present/absent; common/rare; directionality (parallel, multi-directional), length (short/long), morphology of striations (fine, wide, smooth bottom, rough bottom)
High magnification (vertical incident light)	
4. Use-polish brightness	Dull, moderate, bright
5. Use-polish development	Weak, moderate, developed, well-developed
6. Use-polish coverage	Localised, moderate, extensive
7. Use-polish morphology	Reticular; domed; rough-pitted; smooth-pitted; undulating; striated; un-diagnostic
8. Micro-striations	Present/absent; common/rare; directionality; size: depth, width, length
9. Grain fracturing/ scarring/rounding	Present/absent; common/rare; scar type
10. Residues	Present/absent; inorganic/organic; plant/animal

development; (6) use-polish coverage; (7) use-polish morphology; (8) micro-striations; (9) grain fracturing, scarring, and rounding; and (10) residues (Table 6). We focused on documenting and describing the polish formation on individual quartz grains as previous investigations have indicated polish on quartz tools can be diagnostic of worked material (Fullagar, 1986; Knutsson et al., 2015). Polish on quartz tools may be described in terms of variables 4–9 listed above. Use-polish morphology described as "undiagnostic" refers to a stage of use-polish formation that, on its own, is not diagnostic of material worked. Such use-polish may also be described as "weakly developed" with a "localised" distribution.

4. Results

4.1. Experimental usewear/residue reference library

Table 7 summarises the usewear on the experimental grinding stones. The specific wear features documented on each grinding tool are described in the Supplementary Information and are accompanied by colour images of the experimental stones and their corresponding wear and residue traces. Usewear features for each individual tool are summarised in Supplementary information SI Table 1.

All tools displayed distinctive grinding traces and often exhibited usewear that was diagnostic of the class of worked material. The development of usewear varied, depending on several factors, including: (1) sandstone hardness and degree of cementation; (2) the artefact class, particularly how the artefact was used e.g., as an upper, lower or filing stone; (3) physical properties of the worked material, including hardness and elasticity; (4) the mode of use, i.e., grinding and/or pounding; and (5) the intensity and duration of use. The shape (e.g. angular or rounded) and surface weathering of quartz grains within the sandstone formation also affects the formation and appearance of wear. For archaeological specimens, we also considered additional factors that may affect wear including artefact curation, storage, transport, discard and deposition, all or which can generate traces or damage that mimic usewear.

4.1.1. Stone material

All tools displayed distinctive abrasive wear, usually visible macroscopically but certainly visible at low magnification, and forming after relatively short durations of use (< 30 min for most specimens) (Table 8). The softer, weakly cemented Bundanoon sandstone produced the most distinctive macroscopic abrasive wear with distinctive grooves visible after just 5–10 min of use (SI Figs. 1a and 4a). For one artefact (EGS 13), macroscopic grooves could be attributed to stone axe manufacture (based on the groove dimensions) after just 10 min of grinding (SI Fig. 14a–b). However, at high magnification, this sandstone displayed low or no use-polish development, and individual quartz grains often did not display developed levelling or rounding. Thus, diagnostic usewear to indicate the worked material is not likely on archaeological tools made from weakly cemented sandstones. Low frequency of developed wear traces on quartz grains in soft sandstones can be attributed to their removal during use, before the development of diagnostic use-polish on any one grain.

The harder sandstones also displayed distinctive abrasive wear after short durations, usually between 10 and 30 min of grinding. Rather than forming distinctive grooves, macroscopic abrasive wear on the harder sandstones was distinguished by a uniform and levelled surface topography (SI Fig. 15a). Artefacts EGS 2 and EGS 5 (quartzite filing tools used to process wood and bone) took the longest time to develop macroscopic abrasive wear, visible after 40 min of use. The slow development of macroscopic abrasive wear on these artefacts is probably

Table 7
Synthesis of the range of usewear characteristics identified on experimental grinding stones by activity type, excluding data from stones of raw material number 2 (softer Bundanoon sandstone).

Activity	Stereomicroscope			High magnification (vertical incident light)					
	Surface levelling	Grain rounding	Macro striae	Polish morph.	Polish brightness	Polish coverage	Polish development	Fine striae	Grain fractures
Bone filing	min-high	mod-high	Common, parallel	Smooth-pitted; striated	Bright	ext	Developed	Common, parallel	Present
Wood filing	mod	mod	Present, parallel	Domed-pitted; reticular	bright	ext	Developed	Present, parallel	Present
Bone pounding	mod-high	min-high	Present, multiO	Rough-pitted	Dull-bright	loc	Weak	Present, multiO	Common
Seed pounding	min-mod.	mod-high	uncom/absent	undiag/reticular	dull-mod	loc-mod	Weak-mod	uncom/absent	Present
Seed grinding	min-high	mod-high	Present-common	Reticular	mod-bright	loc-ext	Weak-well developed	Common, multiO	Present
Wheat grinding	High	High	Present, multiO	Reticular; striated	Dull-mod	loc-mod	mod	Present, multiO	Present
Stone grinding	High	Mod	Present,parallel	Striated	Dull-mod	ext	Developed	Present, parallel	Common
Axe grinding	High	mod	Present, parallel	Striated; reticular	Bright	ext	Developed	Common, parallel	Present
Pigment filing	High	mod-high	Absent	undulating	Dull-mod	loc-mod	Weak-mod	Present, parallel	Present

min = minimal; mod = moderate; ext. = extensive; undiag = undiagnostic; loc = localised uncom = uncommon; multiO = multi oriented (for striations).

Table 8
Time taken for diagnostic abrasive wear and usewear diagnostic of worked material to develop on the experimental artefacts used to process a range of materials.

Exp #.	Stone #	Artefact type	Worked material	Stroke type/motion	Time required for diagnostic grinding wear	Time required for usewear diagnostic of worked mat.
1	EGS 3	Abrading stone	Bone	Filing	10 min	Did not develop
2	EGS 5	Handstone	Bone	Filing	40 min	120 min
3	EGS 20	Anvil	Bone	Pounding	15 min	30 min
3	EGS 34	Pestle	Bone	Pounding	15 min	30 min
4	EGS 2	Abrading stone	Wood	Filing	40 min	120 min
5	EGS 4	Abrading stone	Wood	Filing	10 min	Did not develop
6	EGS 16	Millstone	Kangaroo grass seeds	Grinding	10 min	90 min
6	EGS 29	Handstone	kangaroo grass seeds	grinding	10 min	90 min
7	EGS 12	Millstone	Warrego grass seeds	Grinding	10 min	65 min
7	EGS 28	Handstone	Warrego grass seeds	Grinding	10 min	65 min
8	EGS 31	Millstone	Warrego grass seeds	Grinding	20 min	150 min
8	EGS 33	Pestle	Warrego grass seeds	Pounding	10 min	85 min
9	EGS 23	Handstone	*Acacia* seeds	Grinding	15 min	120 min
9	EGS 32	Millstone	*Acacia* seeds	Grinding	10 min	120 min
10	EGS 17	Millstone	*Acacia* seeds	Pounding + grinding	15 min	Did not develop
10	EGS 25	Handstone	Acacia seeds	Pounding + grinding	15 min	120 min
11	EGS 19	Mortar	Kurrajong seeds	Grinding	15 min	60 min
11	EGS 24	Handstone	Kurrajong seeds	Grinding	15 min	60 min
12	EGS 1	Abrading stone	Wheat kernels	Grinding	10 min	45 min
12	EGS 15	Millstone	Wheat kernels	Grinding	10 min	45 min
13	EGS 11	Millstone	Coffee beans	Grinding	5 min	Did not develop
13	EGS 37	Handstone	Coffee beans	Grinding	5 min	Did not develop
14	EGS 13/1	Abrading stone	Stone (basalt)	Filing	5–10 min	10 min
15	EGS 13/2	Abrading stone	Stone (dolerite)	Filing	5–10 min	10 min
16	EGS 18	Abrading stone	Stone (basalt)	Filing	15 min	60 min
17	EGS 38	Abrading stone	Stone (sandstone)	Grinding	10 min	60 min
17	EGS 39	Abrading stone	Stone (sandstone)	Grinding	10 min	60 min
18	EGS 35	Abrading stone	Haematite	Filing	< 10 min	10 min
19	EGS 36	Abrading stone	Haematite	Filing	25 min	25 min

related to the relative hardness of the quartzite grinding stone compared with the softer worked material. Both bone and wood are relatively soft materials that do not easily alter the harder quartzite surfaces, and any macroscopic surface modifications take much longer to form than for grinding hard materials.

4.1.2. Artefact class

Abrasive wear formed differently on filing stones and paired stones. The filing stones, which came into direct contact with the worked material, generally displayed a lower degree of surface levelling and infrequent micro-striations (e.g. SI Figs. 1–2, 4–5). The paired stones, on the other hand, generally displayed connected zones of surface levelling with more frequent micro-scarring and micro-striations resulting from the stone-on-stone contact (SI Figs. 6–8, 12–13). An exception was filing stone EGS 35 (used to file haematite), which displayed frequent micro-striations and a levelled surface resulting from the back and forth movement of the hard haematite piece (SI Fig. 17).

Residues occurring on filing stones often displayed distinct alignments, indicating the direction of tool-use. On both paired stones, residues often appeared deep within the interstices of the grains, where they had been smeared and wedged by pressure.

4.1.3. Worked material

Usewear was clearly affected by the class of worked material in direct contact with the sandstone tools. This variation in wear patterns is likely related to the pliability of the material being processed (e.g., elastic/inelastic properties) and its internal composition (i.e., silica content, degree of hydration, and presence of natural lubricants such as oils or fats). The properties of the worked material will affect use-polish formation and the rate at which quartz grains are modified or worn away. At high magnification, the broad classes of worked material could be distinguished on the harder sandstone tools, but the rate of distinctive wear formation was variable (between 10 and 120 min of grinding). EGS 35, a filing stone used to process haematite, and EGS 13 most rapidly developed diagnostic usewear indicative of worked material. Haematite residues were also visible after one contact stroke, and continued to build up on the artefact surface as grinding continued. After 10 min, the surface of EGS 35 appeared highly levelled and the striations were visible macroscopically, occurring both as scratches and alignments in the residue and as furrows in the stone surface (Fig. 3a; SI Fig. 17). At high magnification, the artefact displayed an undulating use-polish and micro-striations were present on individual quartz grains (Fig. 3b; SI Fig. 17c). The other artefact used to process haematite, EGS 36, also displayed similar wear at high magnification, although on this artefact usewear took longer to develop, and was macroscopically visible only after 25 min of grinding (Fig. 3c–b; SI Fig. 18). As with EGS 35, distinctive red pigment particles and smears were abundant, and could not be removed with rinsing or scrubbing. The longer processing time required on EGS 36 to develop macroscopic abrasive wear is probably related to the hardness of the haematite piece that was being worked. Hardness varies depending on the habit (i.e., specular or massive) of the haematite and the relative proportions of iron hydroxide minerals comprising the haematite (e.g., goethite, limonite); as well as operator variance. Residues rapidly accumulated on both artefacts within the first 5 min of grinding and could not be removed easily. If the pigment residues were removed, diagnostic usewear traces could be recognised on tools used for 10–25 min of grinding.

Filing stones used for 60 min to process materials such as bone (EGS 3) and wood (EGS 4) displayed distinctive usewear, clearly visible at high magnification. For the harder sandstones used to file bone, the usewear included a striated, smooth and pitted use-polish, micro-fractures, and abundant, uni-directional micro-striations (Fig. 4a; SI Fig. 2). For the harder sandstones used to file wood, usewear included a domed, pitted and reticular use-polish, micro-fractures and fewer micro-striations (Table 7; Fig. 4b; SI Fig. 5). These wear features became more developed or frequent as filing continued. The usewear observed on the softer sandstones used to file bone (SI Fig. 1) and wood (SI Fig. 4) was not diagnostic at high magnification, although a macroscopically visible groove was visible within 5 min of grinding (Table 8; SI Figs. 1a and

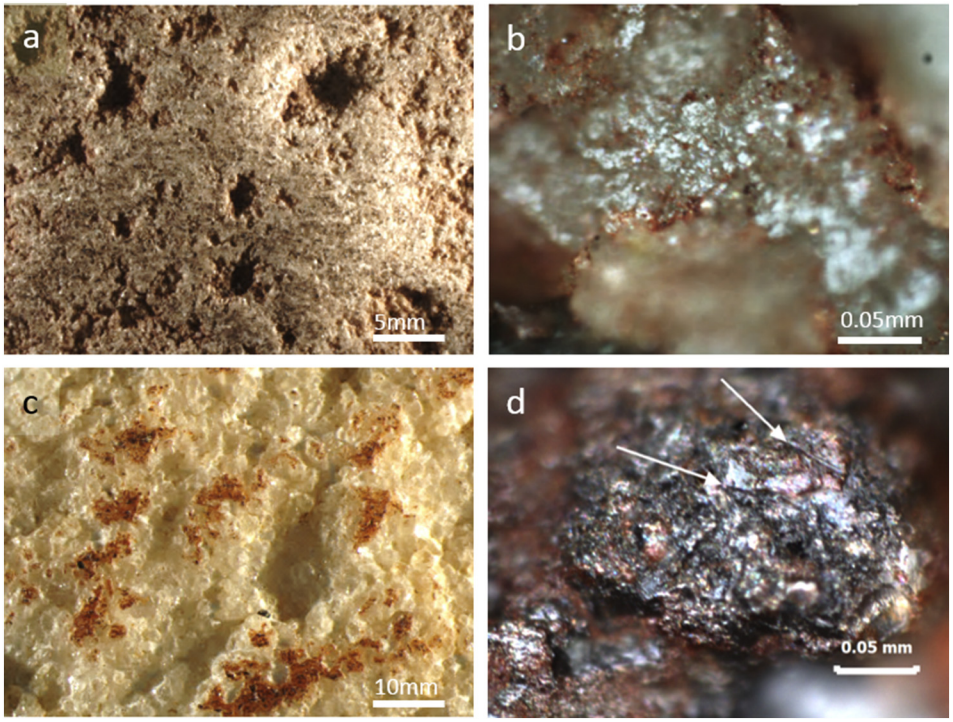

Fig. 3. Usewear and residues on experimental haematite processing tools: a–b) usewear on EGS 35: a) low magnification image of the contact surface displaying a highly levelled surface; b) high magnification image of use-polish with an undulating morphology and scattered pigment residues on the highest grain micro-topographies; c–d) wear on EGS 36: c) low magnification image of the contact surface with red pigment residues on the highest grains; d) high magnification image of undulating use-polish with fine micro-striations (arrows indicate the orientation of striations) and red pigment residues. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4a).

Paired stones made from the harder sandstones and used to process native Australian seeds and wheat kernels displayed diagnostic usewear indicative of worked material. All but one set of tools (EGS 17 and EGS 25) displayed a moderate to high degree of grain rounding and levelling with a bright, reticular use-polish that was visible at high magnification after 60–120 min of grinding (Tables 7 & 8). Other paired stone artefacts used for pounding activities took slightly longer to generate usewear traces diagnostic of worked material. Although all of these artefacts displayed distinctive abrasive wear after 10–20 min of grinding/pounding, developed wear diagnostic of worked material required 75–120 min (Table 8).

Paired stones used to grind seeds sustained the most distinctive use-polish across all surfaces, here described as reticular (Table 5, Fig. 5; SI Figs. 6–8). The extent of developed use-polish, coverage and brightness all varied considerably (Table 7). Although distinctive usewear consistent with seed grinding generally developed rapidly, it was not possible, on the basis of our usewear observations here, to distinguish specific plant taxa. It was possible, however, to distinguish between the processing of hard and soft plant material, including small, hard-cased seeds and softer plant material, on the basis of use-polish at high magnification. The distinction between hard and soft seeds is made because the former (such as *Acacia* and kurrajong) require additional pounding to crack them. Grass seeds, being relatively soft, do not usually require pounding.

Use-polish resulting from the processing of seeds will be restricted to the highest quartz grains with low or no use-polish development within the lower interstices of the sandstone. Use-polish resulting from the processing of softer, more pliable plant materials extended into the lower recesses/interstices of the sandstone as these areas were also in direct contact with the worked materials. However, distinguishing between use-polish from grinding soft and hard plant tissue used in our experiments was only possible after about 60 min.

Interestingly, the hard sandstone used to sharpen the stone axe (EGS 18), also displayed bright reticular use-polish similar to that identified on the plant processing tools (Fig. 6a; SI Fig. 15). Perhaps volcanic stones have amorphous silica or other mineral polishing agents in their matrix (Fullagar, 1991). However, other usewear features can distinguish this tool from those used to process plants; for example, micro-striations were also abundant within the use-polished area resulting from direct stone-on-stone contact and high magnification examination indicated that micro-scarring of individual quartz grains is abundant and far more common on the axe sharpening stone (Fig. 6b). Further distinction between the axe and plant processing tools can, of course, be achieved through residue analysis.

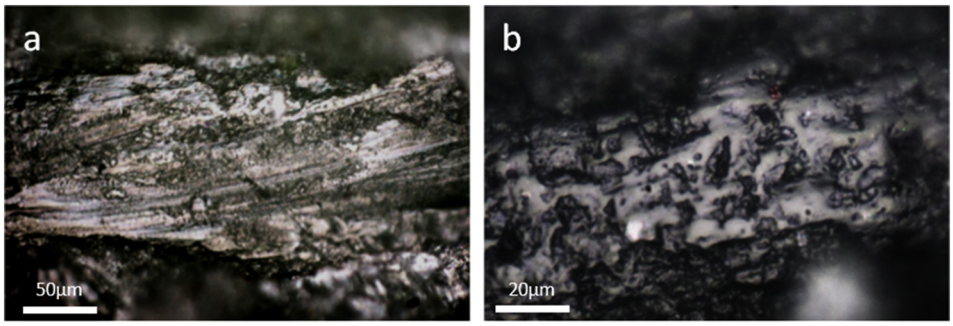

Fig. 4. High magnification usewear documented on bone and wood filing tools made on Kakadu sandstone: a) striated use-polish on bone filing tool EGS 5; b) reticular use-polish with micro-pitting and fine striations on wood filing tool EGS 2.

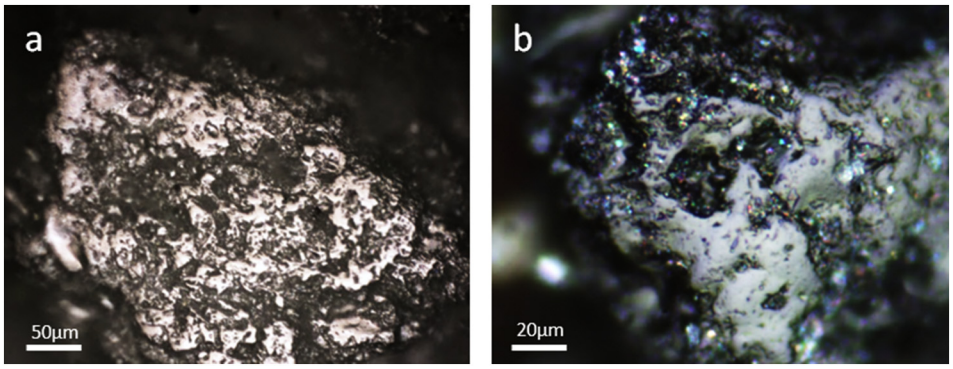

Fig. 5. High magnification images of use-polish on experimental seed grinding tool EGS 28: a) bright, extensive use-polish on highest micro-topographies of a quartz grain, giving the polish a "reticular" or net-like appearance (photographed at ×200); b) use-polish photographed at ×500: micro-pitting is distinguished in the use-polished surface.

4.1.4. Mode of use

The mode of use (or "kinetics" of Adams, 2014, i.e., grinding, pounding, polishing/filing) was also distinguishable on all artefacts even when the worked material remained constant. Stones that were used for grinding or filing usually displayed frequent striations and directionality of the smeared residues. Sandstones that were used to pound materials displayed macroscopically visible impact damage and frequent micro-scarring, visible also at high magnification (SI Fig. 3). Harder sandstones that were used to file or grind softer, more pliable materials, took longer to develop distinctive usewear. Distinctive pounding wear was visible macroscopically after 10 min on tools that were used to crack and crush kurrajong (Experiment 11—EGS 19 and EGS 24) (SI Fig. 11), Acacia seeds (Experiment 10—EGS 17 and EGS 25 (SI Fig. 10) and bone (Experiment 3—EGS 20 and EGS 34 (SI Fig. 3)). Pounding tools were not manufactured from the softer sandstone as initial experiments showed that the stone was too fragile and cracked upon first impact with the hammer.

4.1.5. Duration of use

The experiments show that abrasive wear becomes progressively more developed as grinding continues. These processes were documented both macroscopically and from PVS peels sampled at different stages of use (Fig. 7). The most developed usewear was observed on EGS 28 and EGS 12, used to process warrego grass seeds for 240 min—the longest processing time of any experiments (SI Fig. 7). Grooves within the softer sandstone became deeper and more defined as processing continued.

4.2. Pilot study of usewear on grinding stones from Barapa and Wiradjuri sites

Seven grinding stones, all surface finds, were collected from two regions of southeastern Australia. These included four grinding stones from Wiradjuri sites on the Lachlan River (one upper and three lower stones) made from very hard, indurated sandstone comparable to the experimental Jemalong Ridge specimens; and three grinding stones from Barapa sites (two upper and one lower stone) made from a relatively softer, less well-cemented sandstone (Fig. 1). All seven grinding stones were examined for usewear by examining the microscopic features of PVS peels sampled from the worn regions of the artefact surfaces.

4.2.1. Wiradjuri grinding stones

All four grinding stones from the Wiradjuri sites displayed usewear consistent with the experimental tools used for grinding seeds (Fig. 8; Table 9). All surfaces were highly levelled and displayed macroscopic striations resulting from stone-on-stone contact. Under high magnification, grains displayed well-developed, reticulated use-polish comparable to that recognised on our experimental Jemalong Ridge seed grinding tools. One of the specimens (WGS 20) had use-polish that was restricted to the higher zones of the grains, indicating the processing of hard seed varieties, such as e.g. *Acacia* (Fig. 8a, e). The other three specimens (WGS 22, 29 and 40) (Fig. 8b–d) had a more evenly distributed use-polish across both the higher and lower micro-topographies, indicating seed processing in addition to softer plant materials (Fig. 8f–h).

4.2.2. Barapa grinding stones

All three grinding stones from the Barapa sites had usewear consistent with the processing of hard and soft tissue, including seeds (Fig. 9). All three stones displayed an undulating (rather than levelled) surface microtopography; a feature resulting from the removal of individual grains that had been "plucked" from the weakly cemented sandstone matrix during grinding. The lower grinding stone fragment (BGS 3), had a macroscopically worn depression (Fig. 9a). Small flat zones with fine striations and developed use-polish occur on both upper stones (BGS 4 and 17; Fig. 9b–c), indicating that seed processing is at least part of their function (Fig. 9d–g).

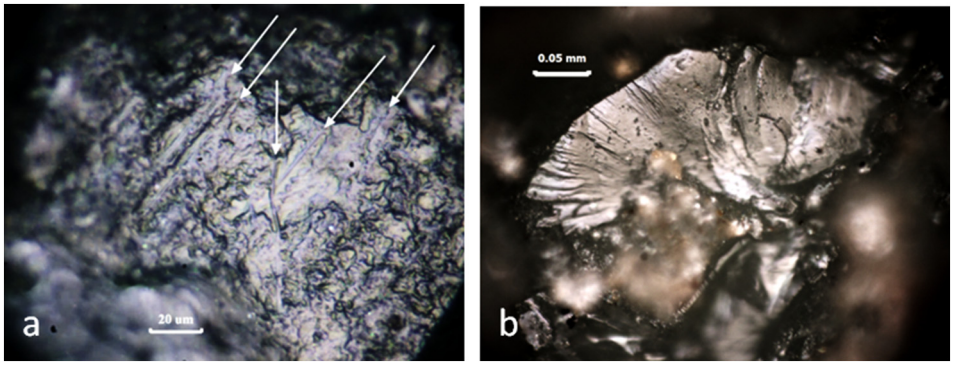

Fig. 6. Usewear on EGS 18 documented under high magnification: a) abundant multi-directional micro-striations on use-polished grains (scale bar = 20 µm, arrows indicate the orientation of striations); b) quartz grain with fresh fracture surface.

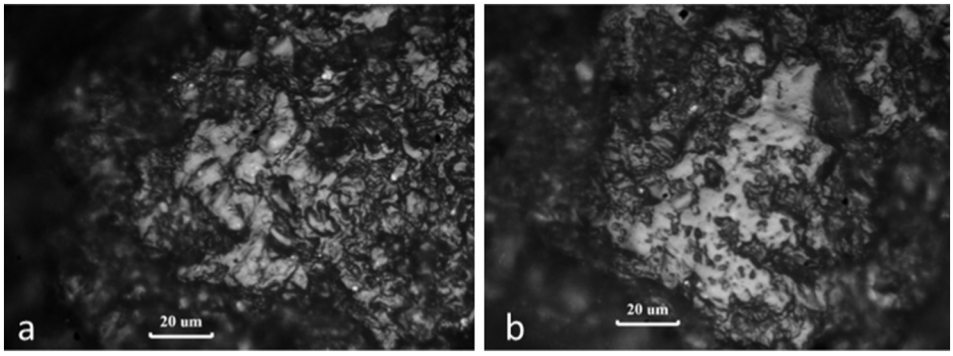

Fig. 7. Polish on experimental seed grinding tool EGS 28 as documented from PVS peels sampled at different stages of use from the same area: a) use-polish development after 65 min of grinding; b) use-polish development after 4 h of grinding.

4.2.3. Summary and archaeological implications

In general, microscopic usewear was more variable on the lower stones compared with that on the upper stones for both the Wiradjuri and Barapa (Table 9). The upper stones had a more even distribution of wear (e.g. use-polish and abrasive smoothing) on the upper and lower zones of the microtopography, most likely the outcome of processing a mix of hard and soft materials. Only WGS 20 (hard sandstone) had evidence of hard seed varieties (e.g. Acacia). The selection and use of hard sandstones for processing hard seeds like those of *Acacia* is predictable because soft sandstones are too weak to withstand the force required to crack hard seeds. Specialised use of hard sandstone in preference to soft sandstone implements may have been a deliberate strategy in response to limited availability of soft (grass) seeds (see below). The presence of reticulated use-polishes in combination with fine striations indicates that seed processing was at least part of their function. Other processed materials (in addition to seeds) could likely include animal tissues in addition to plants; however, residues would need to be assessed to determine these materials more precisely, and

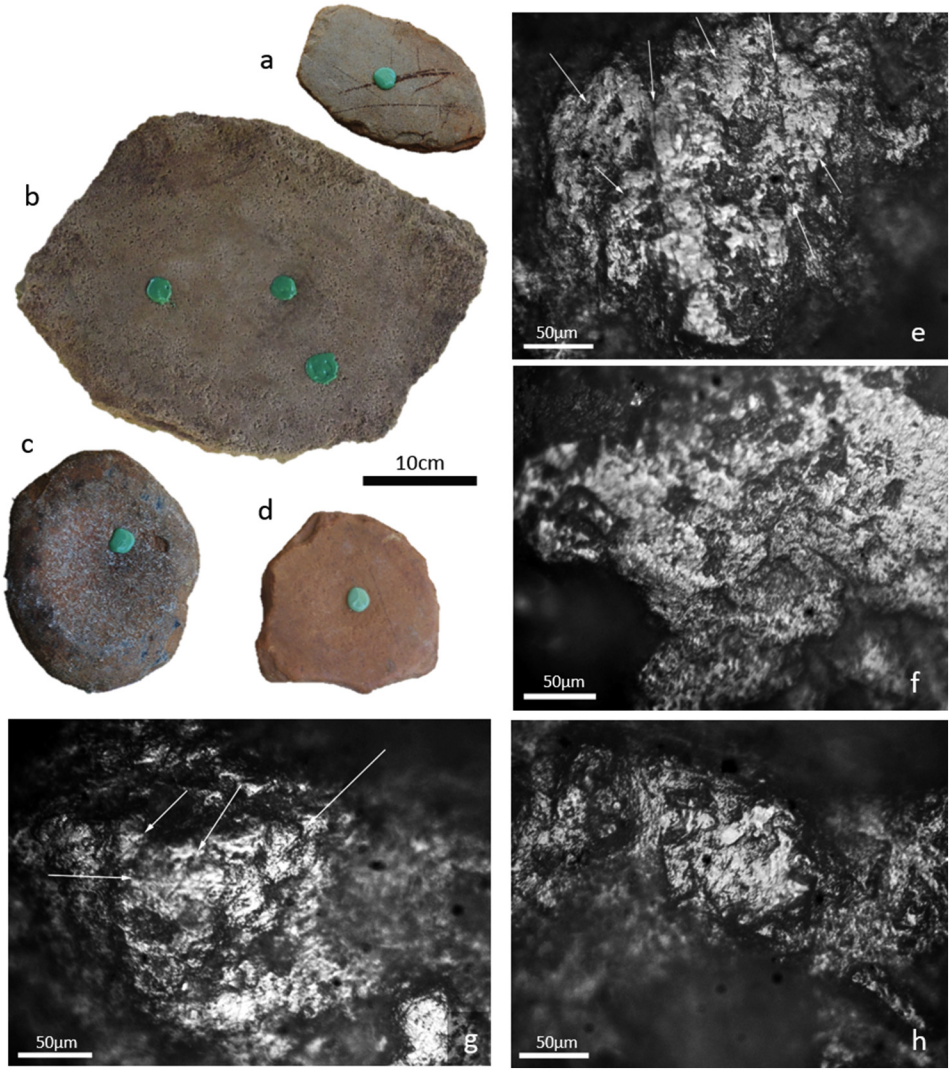

Fig. 8. Grinding stones, fragments and usewear on Wiradjuri tools from New South Wales: a) WGS20; an upper grinding stone with flaked margins; b) WGS22, a flat, slightly concave lower grinding slab; c) WGS29, a mortar stone; d) WGS40, an upper stone with flaked margins; e) reticular use-polish on WGS20 with micro-striations (arrows indicate the orientation of striations) restricted to the highest zones of the grains, indicating hard seed grinding; f) reticular use-polish on WGS22 with polish more evenly distributed on the microstopography, indicating the possible processing of softer materials in addition to seeds; g) reticular use-polish on WGS29 with an even distribution over the microtopography and microstriations (arrows indicate the orientation of striations); h) reticular use-polish on WGS40 with an even distribution on the microtopography.

Table 9
Tool descriptions and likely functions of grinding stones from Wiradjuri and Barapa sites in southeastern Australia. The sandstones from Wiradjuri sites are relatively hard sandstone. The sandstones from Barapa sites relatively are soft.

Grinding stone ID	Tool description	No. of peels	Usewear at high mag	Tool function
WGS 20	Upper stone with flaking around the margin and a levelled surface	1	Deep scratches and restriction of the use-polish to the higher micro-topographies of the grains	Hard seed grinding
WGS 22	Lower stone with flaking around the margin and a levelled surface	3	Even distribution of use-polish on high and low points	Seed grinding plus other softer materials
WGS 29	Lower stone with flaking around the margin and a concave surface	1	Even distribution of use-polish on high and low points	Seed grinding plus other softer materials
WGS 40	Lower stone with flaking around the margin and a levelled surface	1	Even distribution of use-polish on high and low points	Seed grinding plus other softer materials
BGS 3	Lower grinding dish frag. with macroscopic worn depression	2	Siliceous use-polish with fine striations (use-polish in the worn depression is the most developed); individual quartz grains have been plucked from the matrix	Seed grinding
BGS 4	Upper grinding stone made from a water worn cobble with convex section	1	Even distribution of use-polish on high and low points	Seed grinding plus other softer materials
BGS 17	Upper grinding stone, this is made from a harder stone material	2	Even distribution of use-polish on high and low points	Seed grinding plus other softer materials

were not studied further in the present study. The usewear on all stones was consistent with usewear found on experimental seed grinding tools.

Our experiments have shown that harder sandstones do not rapidly form macroscopically visible wear, although after sustained periods of use, the usewear may be diagnostic of processed material when examined under high magnification. The particularly hard sandstones [indurated sandstone to quartzite] may eventually become heavily worn and discarded at site locations where outcropping sandstone is rare. Consequently, we predict that usewear on harder sandstones will increase with their scarcity and distance from the stone source. Our regional results and other regional studies support this hypothesis that tool stone availability is a major determinant of wear intensity (see Fullagar et al., 2015; Hayes, 2015).While stone availability must be taken into account for regional comparisons of wear intensity, the selection and distribution of sandstones by Aboriginal people in southeastern Australia may reflect a response not only to limited availability of hard and soft sandstones but also to the varieties of available hard and soft seed plants, determined largely by climate and other environmental factors. Spatial studies address shifts of plant communities. A hard seed (Acacia) – soft seed (summer grasses) dichotomy developed at Menindee, to the west of Lake Mungo, allowed for examination of food gathering and processing strategies, ultimately influencing residence patterns and the distribution of the archaeological record (Pardoe, 2003).

Today, Menindee and the Darling River are on the edge of the Arid Zone. Prior to 10 ka, this was desert. Mallee (a short, multi-stemmed Eucalypt) and some Acacia would have retreated to the southeast. Grasses would have been perhaps more important than during the Holocene. Willandra Creek, although a smaller river than the Darling, ended in a series of lakes that were open grassland, before the Mallee invaded at the beginning of the Holocene. The Jemalong and other Wiradjuri implements come from open plains that would have been mixed savannah woodland over the whole period of human habitation.

Our focus here, on different sandstone compositions, contributes directly to understanding function of sandstone implements from Pleistocene levels at two other Australian archaeological sites (Hayes, 2015): Lake Mungo in south-west New South Wales (Fullagar et al., 2015) and Madjedbebe rock shelter in northern Australia (Clarkson et al., 2017) (Fig. 1).

The sandstone from Lake Mungo was generally soft and fine grained, and apart from a small local outcrop of quartzite, none of this material is locally available. At Lake Mungo, seed grinding activities were recognised from usewear and residue traces documented on 14 of the 17 analysed sandstone fragments collected from Pleistocene contexts (Fullagar et al., 2015; Hayes, 2015). The ground stone surface morphology may be largely attributed to the nature of tool use (paired stones), the softness of the sandstone and the worked materials (seeds). As sandstone is not locally available at Lake Mungo, many of the tools would have been heavily reduced with extended use-lives, hence evidence of breakage and re-use. Fullagar et al. (2015, Table 1) infer that two of the tools were “recycled”. Similar observations have been made on items from Barapa territory on the Murray River (Pardoe, 2012, 2013).

Sandstone comprising most of the Madjedbebe grinding implements was hard and well-cemented, found locally and ranging from fine grained to poorly sorted coarse grained varieties. The sandstone fragments throughout the sequence exhibited seed-grinding usewear and a range of other functions (see Fig. 12 in Clarkson et al., 2015). They differed from the seed grinding tools at Lake Mungo in form and stone hardness. The relative hardness of Madjedbebe sandstone caused usewear to develop more slowly than on the Mungo sandstones; and locally abundant stone availability likely explains higher expediency and lower grinding stone curation at Madjedbebe.

The Murray River has been a more constant environment throughout glacial cycles; a riverine forest strip surrounded by open plains. Stone assemblages from Willandra Creek (near Lake Mungo) and

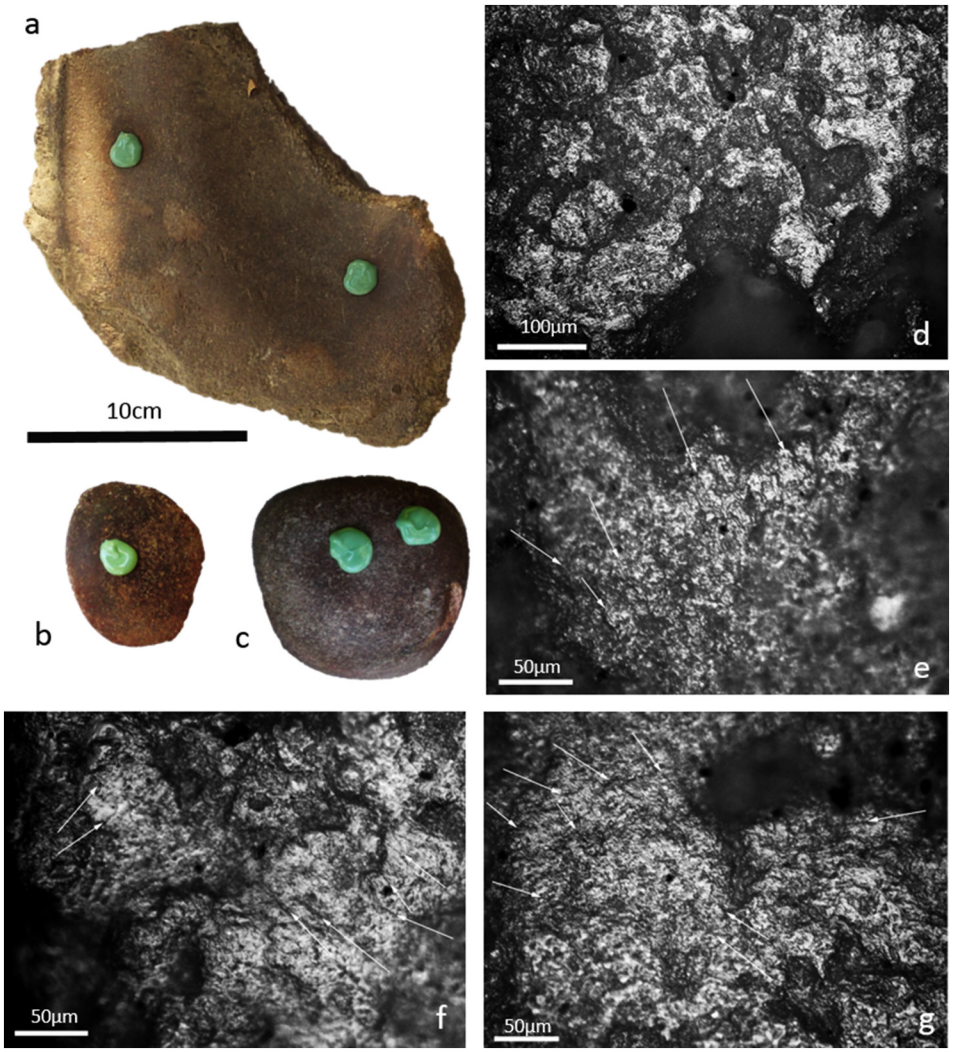

Fig. 9. Grinding stones, fragments and usewear on Barapa tools from New South Wales: a) BGS3, a lower millstone fragment with a well-worn concave surface; b) BGS4, an upper stone fragment with convex section; c) BGS17, an upper stone with convex surface; d) reticular use-polish on BGS3 documented on Peel 1 (far left peel in (a)) with extensive polish on the higher zones of the microtopography, cf. hard seed grinding; e) reticular use-polish and microstriations (arrows indicate orientation of striations) on BGS3, documented on Peel 2 (far right peel in panel (a), sampled from within the depression), note the polish is more extensive in this zone compared with (d); f) reticular use-polish on BGS4 extending into the lower zones of the surface, indicating the working of softer plant materials in addition to seeds; g) reticular use-polish on BGS17 extending into the lower zones of the surface, also indicating the working of softer plant materials in addition to seeds; microstriations (arrows indicate the orientation of striations) are also present and have resulted from stone-on-stone contact.

Murray River share similarities in greater use, recycling and curation contrasted with those from Madjedbebe and Jemalong/Wiradjuri, even though the latter are from such dissimilar environments.

5. Discussion

Grinding stone reference libraries of distinctive and diagnostic usewear have been generated through replicative and controlled grinding experiments on a variety of stone materials (Table 2). The most extensive reference libraries include grinding and pounding tools made from basalt pebbles, cobbles and slabs (Dubreuil, 2004) and different sandstone varieties (Hamon, 2008; see also Adams, 2014).

Dubreuil (2004) focussed on hand-stones and lower grinding slabs made of Levant basalt so that wear could be directly compared to Natufian tools (p. 1614). Dubreuil documented the natural unmodified surfaces of the basalt slabs, as well as the manufacturing wear from pecking and abrasion and subsequent use. This procedure allowed her to distinguish the natural surfaces, working zones, rejuvenated surfaces and post-depositional alterations as they appeared on the archaeological tools. We followed Dubreuil's approach of combining low and high magnification to document three main artefact features: (1) the overall topography of the working surface; (2) surface modifications of the grains; and (3) the presence/absence of striations and shiny areas (cf. polish), and their descriptions (p. 1615).

The reference library for sandstone grinding tools generated by Hamon (2008) was designed to test functional hypothesis related to stone tools from Early Neolithic sites in northwestern Europe. Usewear reference data was obtained from stereomicroscope observations on grinding tools made from modified and unmodified slabs that were used to process a range of ethnographically documented materials. Three features of usewear were documented under the stereomicroscope (up to ×120): (1) levelling of the microtopography; (2) modifications of the interstices (including the presence of residues); and (3) modifications of the angles, edges, profiles and faces of the grains (p. 1506). Our approach complements Hamon's approach by the addition of high magnification observations of micro-striations or use-polish, which may contribute to determination of additional features diagnostic of worked material. Hamon (2008) also found that the speed of usewear formation varied with the type of sandstone (p. 1511) and that fine-grained, well-cemented sandstone was more effective at grinding seeds while poorly cemented, porous and coarse-grained sandstones were more suitable for filing tasks (p. 1506). Our experiments with Australian sandstones support her general findings. The experimental tools made from the weakly cemented Bundanoon sandstone were very effective at filing bone and wood for stone axe manufacture. The usewear on this soft sandstone was distinct from the usewear on the hard sandstones used to process the same materials on both the experimental tools and those examined in the pilot study. The soft sandstone displayed macroscopically visible grooves and depressions, whereas the harder sandstones often did not unless subjected to prolonged grinding sessions. Fullagar and Field (1997:302) have also remarked on the usewear associated with sandstone hardness, stating that “weakly cemented

sandstone is limited in extent by the constant abrasion of quartz grains", whereas quartz grains in the harder sandstones are more likely to remain intact and sustain more wear.

In her synthesis of grinding stone studies, Adams (2014) provided typical wear traces on sandstones used for the processing of (1) soft and hard materials; (2) resilient and pliable materials; and (3) intermediate materials between two stones. She noted that usewear appeared almost immediately, but that features of the wear changed with continued use and re-use (p. 134). Our experimental observations supplement and support these findings.

Despite different methodological approaches in the design and analysis of experimental artefacts it is clear that distinct usewear traces result from working different materials. Each experimental data set indicates that grinding fresh wood and bone creates a more irregular surface topography, where grains become rounded but show low degrees of levelling. Similarly, paired stones used to grind an intermediate material sustain wear with a highly levelled surface, interconnected plateaux and more micro-scarring (see also descriptions in Adams, 2014; Delgado-Raack and Risch, 2009; Dubreuil and Grosman, 2009; Dubreuil et al., 2015; Hamon and Plisson, 2008). All three data sets suggest softer, more pliant materials cushion the contact surfaces between grinding stone, reduce fatigue and abrasive wear and lead to fewer micro-scars and a distinctively smooth, rounded micro-topography, which is not necessarily levelled (see Adams 2014:134).

There are several gaps in our knowledge, which our experiments here did not address, but which demand further study. We did not evaluate manufacturing or post depositional agencies, usewear generated on implements used to process more than one material, or measures of grinding stone tool efficiency (i.e., time motion studies to measure surface erosion rates). Quantification of grinding stone efficiency (e.g. Mildwaters and Clarkson, 2018) will be important for estimating tool use-life and for determining the time involved in generating certain wear traces, particularly those that are visible at a macroscopic level (e.g., grooves). It should be noted that tool use-life is of particular interest among Aboriginal people whose ancestors fashioned and used these implements. The evidence of "elbow grease" from use and recycling are features that fascinate at a personal level no less than at the abstracted realm of lithic studies. Future experiments to add to the usewear reference library will target multiple uses of the same tool (including different grinding actions and multiple worked materials), artefact recycling, grinding stone efficiency, additional sandstone types (both modified and unmodified before use) and additional worked materials. We plan to expand spatial sampling to larger regions such as Arnhem Land and the Murray Darling Basin.

6. Conclusion

We have documented and produced a reference library of usewear and residue traces on sandstone tools following controlled experiments to abrade (file), grind and pound different materials. Through the controlled experiments, we were able to identify key variables that potentially influence usewear formation, such as sandstone hardness/toughness, worked material and duration of use, so that we could build a picture library of traces that may be applicable to Australian Aboriginal grinding implements. We found that macroscopic grinding wear was faster to develop on the weakly cemented Bundanoon sandstone, which often featured deep grooves when it was used as an abrading tool. Macroscopic wear on harder, more tightly cemented sandstones took longer to develop but frequently displayed well developed microscopic usewear and polish that was often diagnostic of worked material. The processing of different materials on the same sandstone variety also produced different usewear traces documented under higher magnification, particularly polish morphologies that are potentially diagnostic of worked material. Well-worn archaeological tools made from harder sandstone varieties, are therefore more likely to possess usewear traces diagnostic of worked material. The deep grooves and depressions documented on the surfaces of tools indicate that they were used extensively to allow such wear to form. The extensive use of these implements without replacement may reflect regional trends such as distance to suitable stone sources.

The controlled experiments were also useful for determining the effectiveness of certain sandstone varieties at grinding and/or filing specific materials. For example, the Bundanoon sandstone was a very effective abrader for filing stone, bone and wood, but was ineffective as a handstone or millstone. When this stone was used to grind coffee beans (large hard seeds), the stone wore away quickly and the resulting ground coffee mixture was extraordinarily gritty and unsuitable for human consumption. The harder sandstones were less effective than the soft sandstones at filing, and took far longer to produce a similar effect on the worked material. In one case, additional sand had to be added to the stone surface to help abrade the worked material. These harder sandstones, however, were very effective at grinding harder materials such as most grass seeds. Microscopic polish developed very quickly on the working surface of these tools, which were more durable than the softer stones.

The usewear and residues documented on our experimental grinding and pounding tools supplements modern reference libraries that are necessary for standardisation of methods, observations and interpretations of archaeological tools. Although our experiments are not comprehensive, previously published experimental data from Australia and other regions have shown that diagnostic usewear traces can be identified on grinding implements made on sandstone, granite, basalt and other stone materials. The pilot study presented here has highlighted sandstone hardness as a significant variable in understanding the function of Australian grinding stones.

Disclosure statement

Authors declare no financial support or relationships that may pose conflict of interest in the submitted manuscript.

Acknowledgements

Funding for the experimental grinding workshop was provided by Byangee Academic Retreat, Yadboro, New South Wales. We thank Chris Clarkson, Lesley Head, Penny Taylor and Birgitta Stephenson for help during the workshop. We would also thank Brian Jones and Jose Abrantes for help with XRD and SEM analysis of sandstone. The Barapa and Wiradjuri grinding implements were analysed with the permission and support from Norman Moore, Neville Whyman and Sharnie Hamilton of Barapa Nation and Leeanne Hampton and Linton Howards of the West Wyalong Local Aboriginal Land Council. E. Hayes was funded by an Australian Postgraduate Award. We thank two anonymous reviewers for helpful comments to improve this manuscript. Studies of grinding implements with Barapa, Wiradjuri and Ngiyampaa were part funded by an Australia Research Council grant (LP130100748).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2018.04.021.

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